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NONLINEAR WAVE PROCESS HIERARCHIES AND THE CYCLIC DEVELOPMENT OF QUASI-ORDERED STRUCTURES IN TURBULENT SHEAR FLOWS

Final Report

July 1, 1977 - June 30, 1979

Roberto Vaglio-Laurin

NYU/DAS-79-18

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The nonlinear wave interpretation and description of the large-scale coherent structures commonly observed in free as well as bounded turbulent shear flows is discussed. The experimentally observed cyclic development of nonlinear two-dimensional vorticity concentrations in homogeneous, incompressible, free mixing layers is linked to the growth/equilibration of finite amplitude, spatially amplifying instabilities and their cyclic regeneration under the action of... intrinsic secondary instabilities evoked by flow nonlinearity. The mathematical modeling of such nonlinear behavior in terms of matched asymptotic

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expansion solutions of the Navier-Stokes equations, being reported under separrte cover, is reviewed. The relevance of the physical viewpoint and the mathematical model to more general turbulent flows is examined and supported by an analysis of selected, conditionally sampled, measurements in transitional and turbulent boundary layers. On that basis, a dominate role of specific nonlinear wave processes is indicated, and the approach to their systematic mathematical modeling from first principles is outlined.

I. INTRODUCTION

Under Contract F-49620-77-C-0119 a program of theoretical research, focused on a non-linear wave interpretation and description of the large scale coherent structures commonly observed in free as well as bounded turbulent shear flows, has been conducted during the period 1 July 1977 through June 30, 1979. Whereas the accumulated body of experimental evidence, largely of a qualitative visual nature (Refs. 1, 2, and 3), has forcibly demonstrated a dominant role of those structures in the production and sustenence of turbulence, the title effort has been concerned with the development from first principles of a physical/mathematical model capable of quantitatively describing the role of the structures in terms of the development and cyclic history of the associated non-linear concentrations of transverse mean vorticity. Upon generalization and validation against experiments, such a model promises to yield the systematic quantitative understanding prerequisite to possible control of turbulent flows of practical interest.

The first year effort under Contract F-49620-77-C-0119 was largely focused on the elaboration of a novel mathematical model descriptive of the non-linear development of vorticity concentrations in two-dimensional mixing layers. Several results were validated against experiments and reported in Ref. 4. Since that time the mechanism for cyclic agglomeration, and thus reproduction, of mixing layer structures has been identified; hence, the conceptual model definition has been completed for that class of flows. In addition, the vorticity concentration mechanism, and the attendant mathematical model evolved for mixing layers, have been

evaluated in the context of boundary layers. Careful data analyses have indicated distinct relevance of the physical viewpoint and mathematical approach for this second class of flows, to the extent that a conceptually unified interpretation of the dominant processes revealed by recent and classical conditionally sampled measurements in nominally two-dimensional transitional and turbulent boundary layers can be constructed.

Whereas the details and validation of the mathematical model for two-dimensional mixing layers are being presented in a separate paper (Ref. 5), the present report focuses on the results obtained during the second year of the effort and their implications with regard to 1) the novel, rapidly growing, physical understanding/modeling capability being evolved, and 2) the conceptually unified interpretation of diverse problems provided thereby.

II. ACCOMPLISHMENTS OF THE RESEARCH EFFORT

The most notable advance in modern turbulence research resides in the experimental finding that turbulent flows of simple geometry are not as chaotic as previously assumed: some order prevails in the motion, with observable chains of events/structures recurring randomly but with statistically definable mean periods (Refs. 1,2,3). These large scale structures were first observed in free shear layers, where they take the appearance of breaking two-dimensional waves (or roller/vortices), which convect at nearly constant speed and increase their size and spacing discontinuously by amalgamation with neighboring ones (Figures 1 and 2, Ref. 7). The nature and development of the structures is insensitive to Reynolds number, and remains basically the same in the transitional as well as in the fully developed turbulent portions of the flow. The fully developed turbulent portion is distinguished only by the onset and cascade of three-dimensional, Reynolds number-and external disturbance-sensitive, instabilities, which evolve within, and are amplified by, the transverse mean vorticity concentrations associated with the large scale structures. As a result the production of Reynolds stress and turbulence do not take place as stationary random processes but, instead, are phase related to the transit and evolution of the structures. Mean flow growth also reflects directly the same coherent processes; to paraphrase F.K. Browand "the pairing interactions do not take place <u>in</u> the mixing layer, but rather they <u>are</u> the mixing layer in a very essential way."

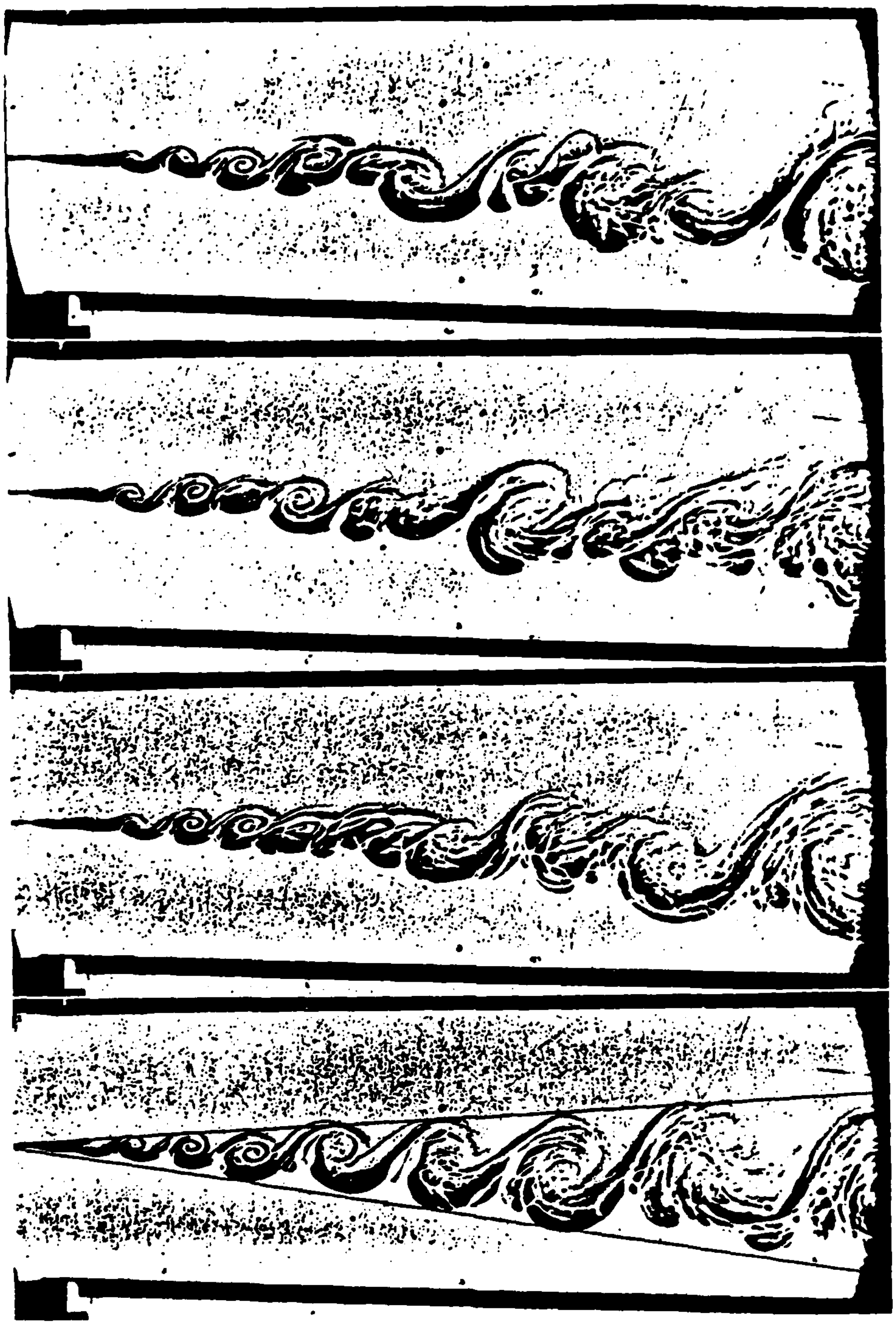

Fig. 1 Shadowgraphs of a free mixing layer taken at random times (from Ref. 7).

Reflection on the noted experimental results strongly suggests that deterministic, coherent, nonlinear wave mechanisms are operative. A review of relatively old measurements of the nonlinear stages of free shear-layer transition fully supports the view (Fig. 3, Ref. 8). In fact, the experiments prove quite revealing for they show that the wave development cannot be explained by classical weakly nonlinear stability/wave models (e.g. Ref. 9). Several sequential stages are indicated. Following an initial spatial disturbance amplification consistent with linear theory (stage 1), nonlinear effects arise at surprisingly small amplitudes of the fundamental ($A \simeq 10^{-2}$), and result in forced subharmonics/harmonics (which amplify at rates approximately 1.5 times as large as that of the fundamental) as well as in a developing transverse vorticity concentration (stage 2). The forced waves are certainly intrinsic to, and driven by, the fundamental as they equilibrate together with it (stage 3). The equilibrium stage persists until two vorticity concentrations exist side by side; the subharmonic, which represents the fastest growing instability for a row of parallel line vortices (Ref. 10), then resumes growth (stage 4), leading to

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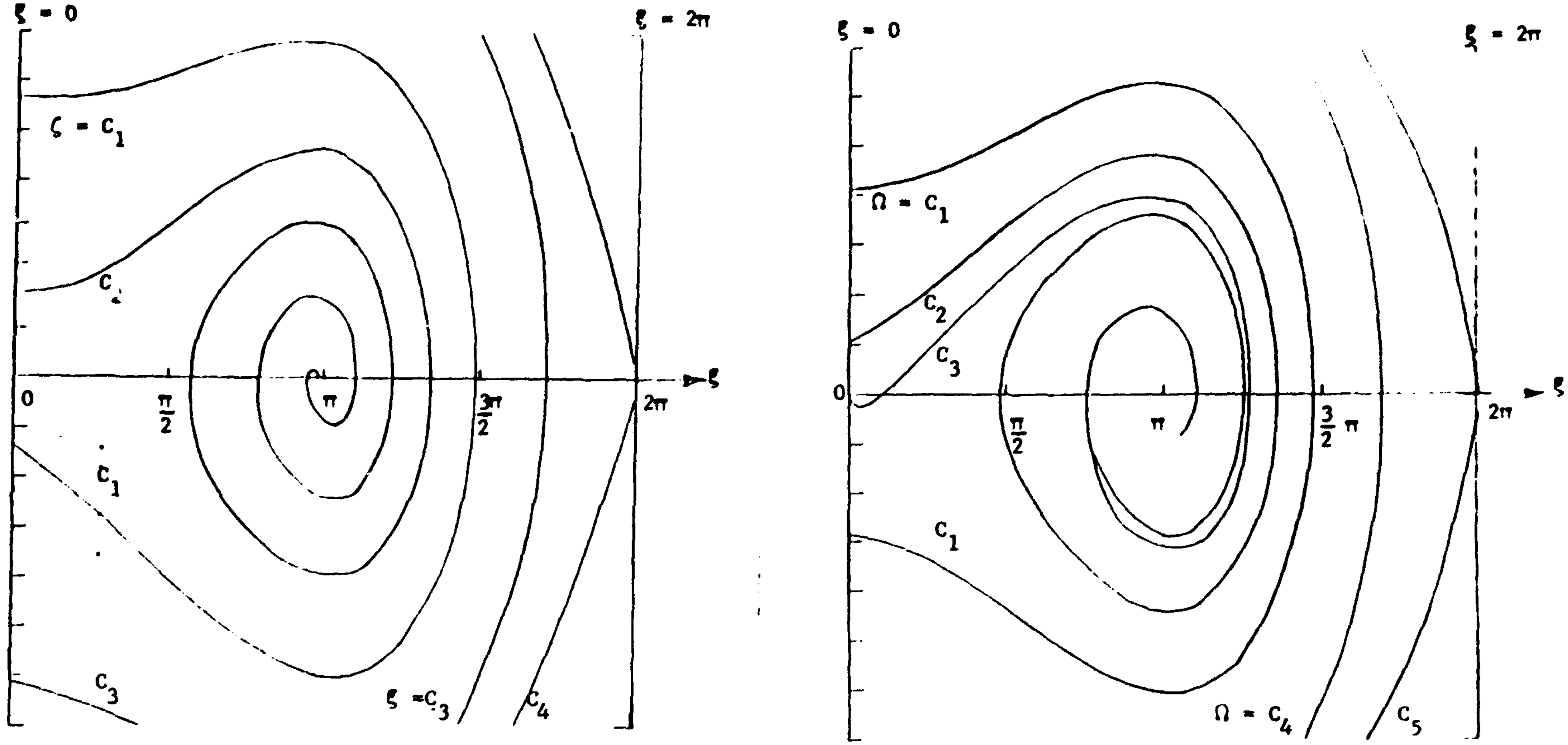
agglomeration of the two vortices and doubling of the mean flow width (stage 5). Upon this doubling the wavenumber and frequency of the subharmonic become eigenvalues of the mean flow; accordingly, the cycle of nonlinear wave development can be reinitiated and repeated (stage 6 and so on).

The key to first principle modeling of the noted sequence of stages resides in the observation that in a neighborhood of the critical layer, where mean flow velocity equals wave phase velocity, fluid elements are continuously exposed to essentially the same wave phase and, thus, are subject to cumulative non-linear effects. Admittedly viscosity tends to counteract (diffuse) these effects; however, its action is not necessarily dominant at all wave amplitudes, as assumed in classical linear and weakly-nonlinear theories. Order of magnitude analysis of the Navier-Stokes equations readily reveals that nonlinear effects in the neighborhood of the critical layer assume a dominant role vis-a-vis viscous effects at the modest wave amplitudes ($A \simeq 10^{-2}$) exhibited in the experiments. Beyond this threshold the actual growth of the small, but finite, amplitude wave can only be modeled by novel, first principle matched asymptotic solutions of the Navier-Stokes equations, such as were advanced for neutral waves in Refs. 11, 12 and have recently been derived for amplifying waves in Refs. 5, 6. These solutions, which (upon second tier asymptotic expansions and simultaneous coordinate perturbations) can be evaluated semi-analitically in both the strongly nonlinear inner (critical layer) region and the weakly nonlinear outer region, reproduce the vorticity roll-up (Figs. 1 and 4) as well as the attendant mean flow



(a) (b)

Fig. 4 Nonlinear stages of free shear-layer transition. Wave-fixed pattern of vorticity concentration near the critical layer predicted by the analytical model for a two-dimensional, spatially (?) growing, finite amplitude instability of wavenumber α_r and frequency β. (a) The coordinate system [ξ = ($\alpha_r x - \beta t$)], [] in the inner (critical layer) region as the instability approaches equilibration. (b) The attendant constant vorticity contours predicted by the inner solution (from Ref. 5).

distortion and the level/amplification of the subharmonics/harmonics observed in stage 2 of the experiments (Fig. 3). Their elaboration to higher orders, exploiting multiple time scales techniques, indicates that a cubic Schrödinger equation governs the finite amplitude equilibration of the wave system, in accord with the experimental evidence of Ref. 8 (Figure 3, stage 3). Whereas the exact solutions of the Schrödinger equation (Ref. 13) predict that an arbitrary smooth initial wave packet eventually disintegrates into a definite number of permanent wave packets (envelope solitons) stable to collisions, the model rigorously leads to the classical analysis (Ref. 10) of the vortex row instability manifested in stage 4 and, finally, to the numerical Navier-Stokes description (Ref. 14) of the vortex agglomeration observed in stage 5. Thus, the entire nonlinear wave cycle is amenable to rigorous modeling by the admittedly complex, but systematic, analytical process presented in Refs. 4,5 and schematically depicted in Fig. 5. Time averaging of the attendant momentum transports at a fixed space location directly yields the Reynolds stresses and, therefore, the constitutive coefficients to be employed in consistently averaged equations which provide the user-oriented tool for overall flow analysis.

Whereas experiments employing proper conditional data sampling (Ref. 15) show that, in practice, the coherent eddies arise more commonly than hitherto observed, and that their two-dimensional character is preserved even in the presence of strong external small-scale buffeting, the confidence in the proposed physical viewpoint and the microscopic as well as macroscopic models attendant thereto is strenghtened significantly. The tool

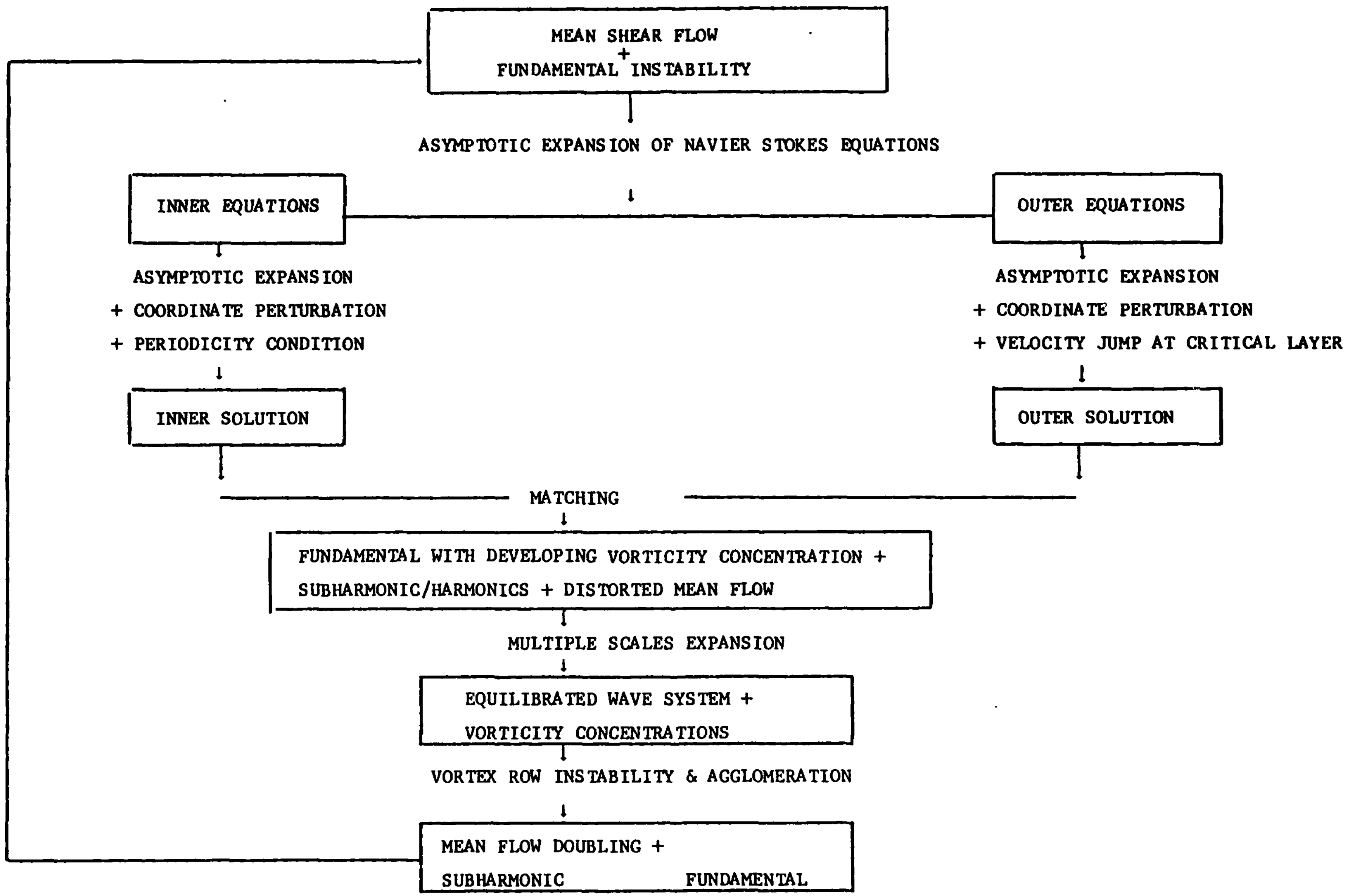


Fig. 5 Block diagram of the analytical model describing the life cycle of two-dimensional finite amplitude waves in free shear layers.

for systematic, first principle, sensitivity and scaling studies of transitional and turbulent two-dimensional mixing layers appears to be on hand; in fact, preliminary calculations indicate that the puzzle concerning the reduced spreading rates measured for homogeneous, isoenergetic, compressible mixing layers (Ref. 16) may be resolved in terms of a corresponding reduction in the amplification rate of the eddy producing, nonlinear instabilities, as a suitably defined Mach number exceeds unity.

The apparent success in understanding and modeling the two-dimensional mixing layers clearly begs the question: how generally may one apply the viewpoint of dominant large-scale coherent non-linear wave processes, cyclically evolving under the action of intrinsic bounded secondary instabilities, to fundamentally describe turbulent flows at large? A selective review of recent and classical experiments keyed to this question yields a positive conclusion (see below) and, thus, provides strong heuristic support to the major conclusion of the research effort, viz. the physical-mathematical framework outlined above provides the basis for conceptually unified analysis, understanding, and eventual control of turbulent flows.

Whereas recent experiments with axisymmetric transitional and turbulent jets (Ref. 17) and wakes (Ref. 18) forcibly exhibit large scale structures possessing nature, history and role conceptually identical to those of the "Brown-Roshko" vortices in mixing layers, the application of the proposed unified viewpoint and modeling approach to general free shear flows is justified except for modifications of detail. Admittedly the details may

prove rather laborious; however, their elaboration entails a once for all effort, whence information pertinent to overall model constitutive coefficients/parameters may later be extracted and systematically applied to the realistic solution of diverse practical problems.

The extension to boundary layers seemingly poses a more perplexing problem. Whereas coherent structures have been observed repeatedly (Refs. 1, 2,3), and their nature/history qualitatively described at least on a visual basis, an overall mechanistic interpretation of the attendant processes is still lacking. To quote from Ref. 19: "No one has yet been able to patch together a comprehensive theory covering the entire instability-transition regime. It is significant that almost none of the nonlinear stability analyses compare results with experimental data -- they almost exclusively are presented as qualitatively representing the post-primary stages of breakdown." In this vein the classical low speed transition measurements of Ref. 20 have qualitatively been interpreted in the light of weakly nonlinear theory (Ref. 9), even though detailed examination (Ref. 6) reveals several discrepancies between the model and the observations of a controlled, amplified, three-dimensional disturbance with spanwise amplitude modulation (Fig. 6). First of all finite amplitude effects (i.e. distinct amplification rates of r.m.s. u'-fluctuations at peaks and valleys, different from the common rate predicted by linear theory) arise suddenly and at surprisingly low disturbance levels $[(u'/U_1) \simeq 10^{-2}]$ as shown in Fig. 7. Secondly, while the measured wave phase velocity and phase distributions across the boundary layer show little change until breakdown is approached, the spanwise modulated distributions of streamwise r.m.s. velocity (Fig. 8)

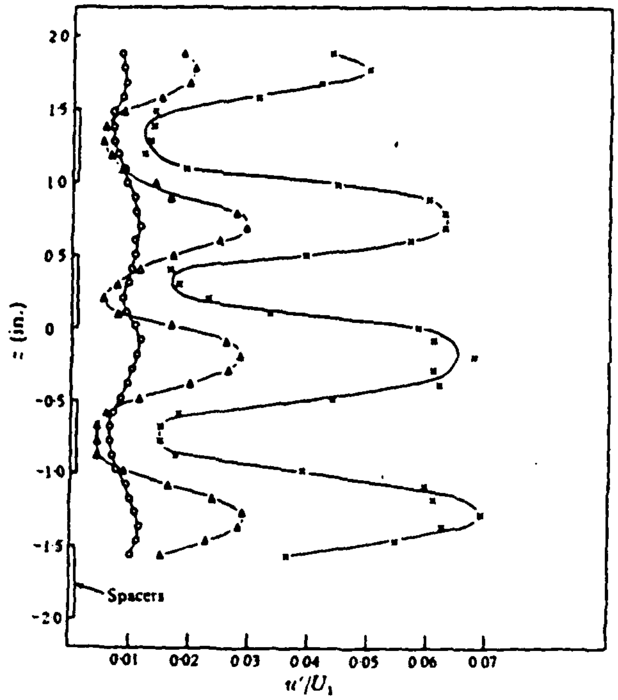


Fig. 6 Experiments on controlled flat plate boundary layer transition. Spanwise distributions of r.m.s. u'-velocity at fixed (y/δ) and various downstream locations: o, $(x-x_o)$ = 1 in.; Δ, (x-xo) = 4 in.; x, $(x-x_o)$ = 5.5 in. (from Ref. 20.).

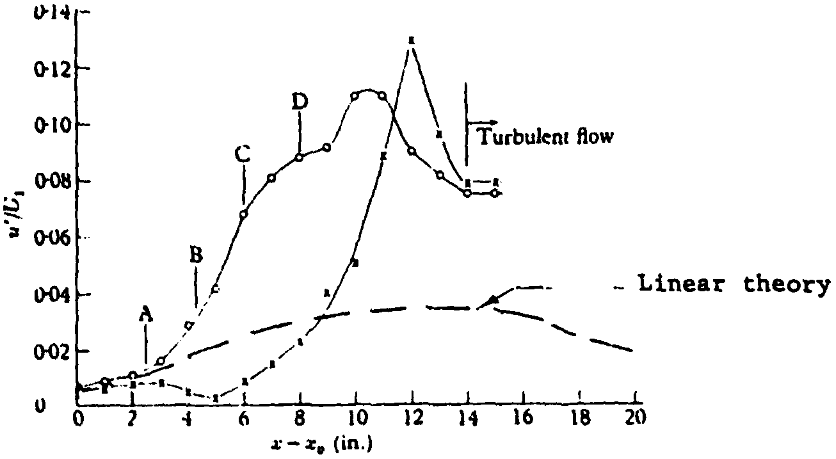


Fig. 7 Experiments on controlled flat plate boundary layer transition. Streamwise distributions of r.m.s. u'-velocity at fixed (y/δ) and various spanwise locations: o, z =- 0.2 in (peak); x, z =- 0.75 in. (valley) (from Ref. 20).

and spanwise mean velocity exhibit different apparent growth rates at different locations (y/δ) in the layer. The evolving nonlinear effects are seen to influence a confined region of dimensionless transversal extent (y/δ) < 1 (Fig. 8), which grows with the disturbance amplitude. Moreover, the (y/δ) position for maximum spanwise modulation of r.m.s. velocity within the affected region is seen to migrate in rough synchronism with the shift of the critical layer due to "secondary" distortions of the mean velocity profile (Fig. 9). Whereas the pronounced magnitude of these "secondary" shifts is symptomatic of strongly nonlinear behavior, a further detailed scrutiny of the data is prompted and, by that process, a third discrepancy between observations and weakly nonlinear theory is revealed, namely: quantities considered of second order in the theory achieve experimental magnitudes comparable to those of quantities considered of first order. The convergence of the series expansion underlying weakly nonlinear models is then impugned, and the requirement for a matched expansions approach, along the lines presented in Fig. 5, is evidenced.

The relevance of the proposed nonlinear wave viewpoint in resolving the noted features of controlled boundary layer transition measurements is supported by the same three counts that indict the classical analysis. First the nonlinear effects arise at the disturbance amplitude level indicated by the nonlinear critical layer model (Fig. 7). Secondly, this model is predicated on a growing, but confined, domain of strongly nonlinear behavior such as in Fig. 8. Thirdly, the model predicts that the evolution of the complex wave envelope is governed by a cubic Schrödinger

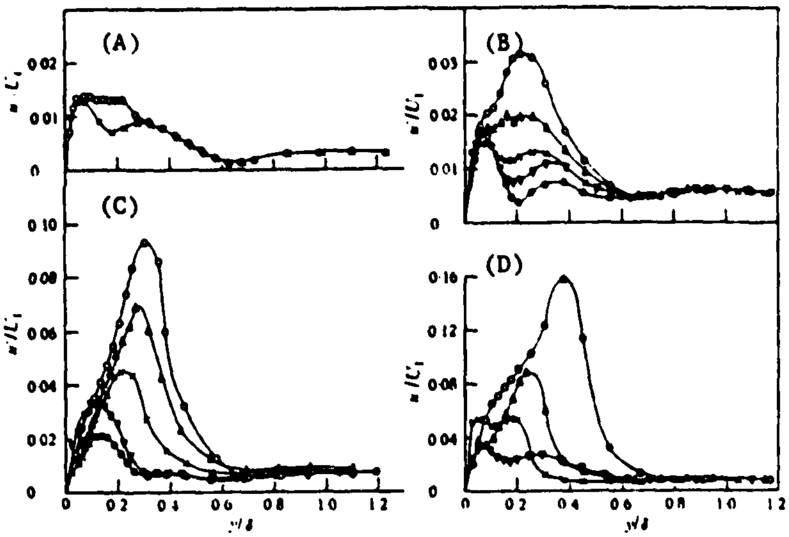


Fig. 8 Experiments on controlled flat plate boundary layer transition. Distributions of r.m.s. u'-velocity across boundary layer at the streamwise stations A,B,C,D defined in Fig. 7 and various spanwise locations: o, z =- 0.2 in. (peak); Δ, z = - 0.35 in.; x, z =- 0.45 in.; ∇, z =- 0.55 in.; •, z = - 0.65 in. (valley) (from Ref. 20).

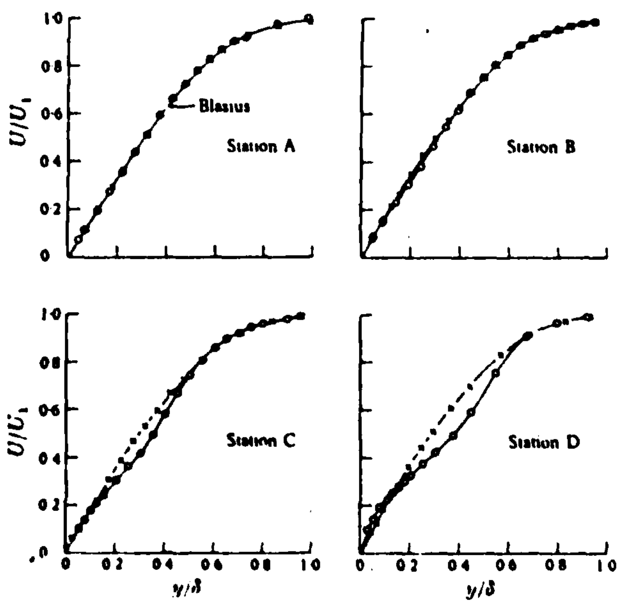


Fig. 9 Experiments on controlled flat plate boundary layer transition. Distributions of mean velocity across boundary layer at the streamwise stations A,B,C,D defined in Fig. 7 and two spanwise locations: o, z =- 0.2 in. (peak); x, z =- 0.75 in. (valley) (from Ref. 20).

equation, whose exact solutions (Ref. 21, Fig. 10) are known to reproduce the growing spanwise modulation of disturbance amplitude evidenced in Fig. 6, as well as to include (according to the outline presented in connection with free shear layers) intrinsic, movable, growing, first order mean flow distortions such as those of Fig. 9. To be sure certain extensions and elaborations of the matched, inner and outer solution model, developed for two-dimensional free shear flows, are required. Specifically, the spanwise-periodic amplitude modulation, as well as the finite curvature of the mean velocity profile at the critical layer, must be reflected in a new choice of the parameter governing the asymptotic expansions as well as the coordinate perturbations in the inner and outer regions so that the non-linear critical layer solution retains the spanwise coherence indicated in Fig. 6, while it forces bound-wave perturbations having the large apparent growth rates exhibited in Figs. 7 and 8. The matching bound-wave perturbations in the outer region can then reproduce counter-rotating streamwise vortices, adjacent to the wall and to the spanwise modulation peak, which result in the inflectional distortions of the mean velocity profile shown in Fig. 9 and the shifting (y/δ) positions for maximum spanwise modulation of rms velocity shown in Fig. 8. In this context, all major discrepancies between theory and experiments upstream of the breakdown station are seemingly reconciled. However, the mechanistic description of the transition process remains incomplete: the problems of breakdown, ensuing boundary layer response and subsequent cyclic sustenance of turbulence beg realistic resolution and modeling. Fortunately, upon some reflection, the nonlinear wave viewpoint appears to remain operative and to offer the conceptual framework for closing the data interpretation and modeling loop as discussed below.

(a)

(b)

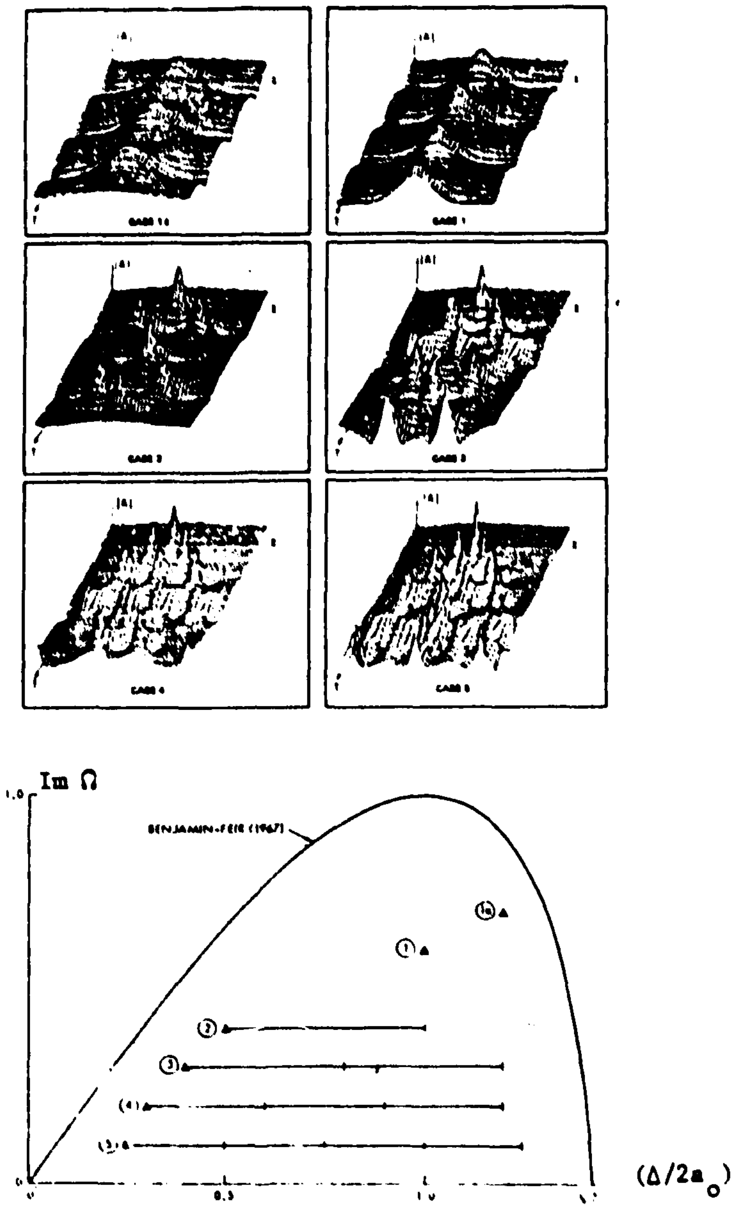


Fig. 10 Solutions of the cubic Schrödinger equations describing the long time (T) evolution of the envelope amplitude $|A|$ for a nonlinear wave subject to Benjamin-Feir modulational instability and initial conditions $T = 0$, $A = a_o\,(1-0.1\cos 2\pi\Delta X)$. (a) Examples of simple and complex evolutions calculated for different values of the perturbation wavenumber Δ. (b) Map of the normalized perturbation wavenumbers ($\Delta/2a_o$) used in the reported cases 1a through 5 and their harmonics ($n\,\Delta/2a_o$) which fall within the domain of Benjamin-Feir instability (from Ref. 21). Note that the complexity of the response at (a) increases as the number of unstable harmonics ($n\,\Delta/2a_o$) increases.

The intrinsic development of inflectional mean velocity profile distortions (Fig. 9) during the non-linear phases of boundary layer transition has long been recognized as the cause of wave breakdown. Attendant to the spatially growing inflections are free shear layer instabilities of related scale and amplification rate* which, in rapid sequence, tend to generate locally the nonlinear processes described in connection with the free shear layers, i.e. vorticity concentration/agglomeration and concomitant mean flow perturbation. Whereas the integral effect of those processes is a localized finite amplitude stress pulse, the formation of the "turbulent spots" upon breakdown, and their subsequent growth and coalescence with one another to form a fully developed turbulent boundary layer, must constitute the manifestation of the overall, pulse-induced, boundary layer response. The view is supported by numerous recent experiments (e.g. Refs. 2,3,22), where turbulent spots have successfully been evoked by point-pulsing subcritical as well as supercritical laminar boundary layer flows. The salient findings of these experiments are: 1) the evoked spot depends on the embedding boundary layer, but not on the generating disturbance; as such, it rapidly attains a universal self-similar shape, which grows at a roughly linear rate. 2) In a supercritical boundary layer the spot is accompanied by a trailing packet of Tollmien-Schlichting waves which possess strong spanwise amplitude modulation, attendant tendency to breakdown, and consequent capability to generate a new spot near the "wing tips" of the original one (Fig. 11, Ref. 22). 3) The

* The extension of the model of Refs. 4,5 to describe nonlinear instabilities in space/time dependent free shear layers portends no ostensible conceptual difficulty.

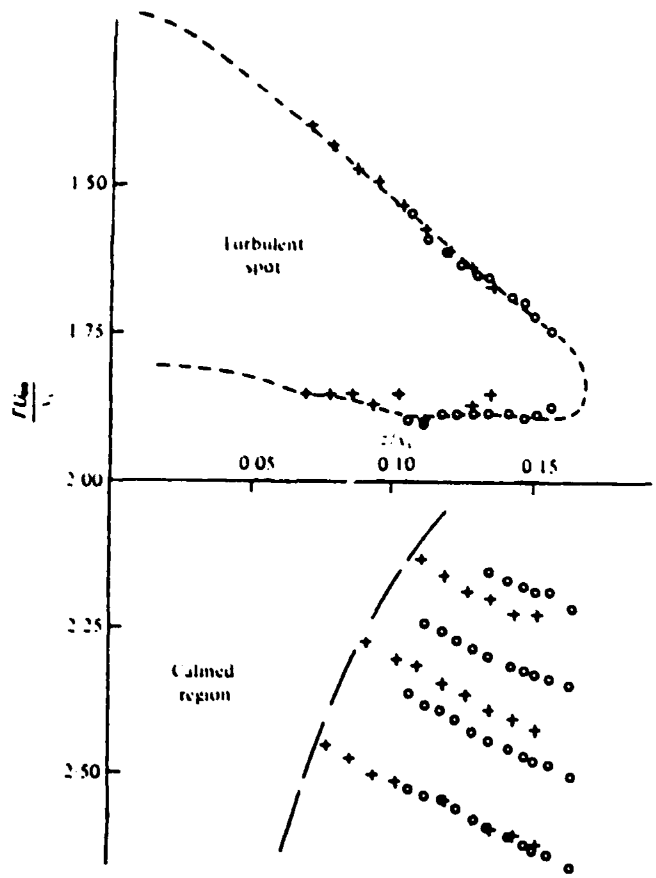


Fig. 11 Experiments on transitional spots artificially evoked in a supercritical laminar boundary layer. Top view of the dimensionless geometrical relationship between the contour of the spot and the fronts of the trailing Tollmien-Schlichting wave packet observed at two distances x_s downstream of the spark: +, x_s = 2 ft.; o, x_s = 3 ft. (from Ref. 22).

spots so generated persists as basic flow modules in the fully turbulent boundary layer, and, in fact, their proper streamwise sequencing reproduces the well known mean velocity profile. 4) The lifetime of the mature spots is limited by the onset of shear layer instabilities at their highly contorted interface with the external flow (see Fig. 12e, and Falco's contribution to Ref. 2). Thus, a deterministic hierachy/sequence of nonlinear wave processes is again indicated.

The observed coexistence of the turbulent spot, with growth roughly linear in time, and the trailing Tollmien-Schlichting wave packet, with growth exponential in time, clearly reflects the expected decomposition of the boundary layer response into two parts, respectively associated with the continuum and the discrete spectra of eigenfunctions for the considered system. Such decomposition, into self-preserving elements of diverse time dependence, is predicted even by a linear analysis. In fact, the three-dimensional wave packet resulting from the discrete spectrum portion of the boundary layer response to a pulsed point-source has been determined in the linear limit (Ref. 24). Nonlinearity, manifested by the distinct vorticity concentrations associated with the spots (Fig. 12), as well as by the eventual breakdown of the trailing Tollmien-Schlichting wave packet, apparently acts as a bandpass filter singling out for survival and amplification those dominant components of the continuum and discrete responses which initially are above the nonlinear threshold and subsequently remain dually compatible with each other as well as with the attendant mean flow perturbations. A model reflecting this state of affairs may be constructed by the following sequence of steps: 1) elucidate the nature of the wave packets which result from the continuum

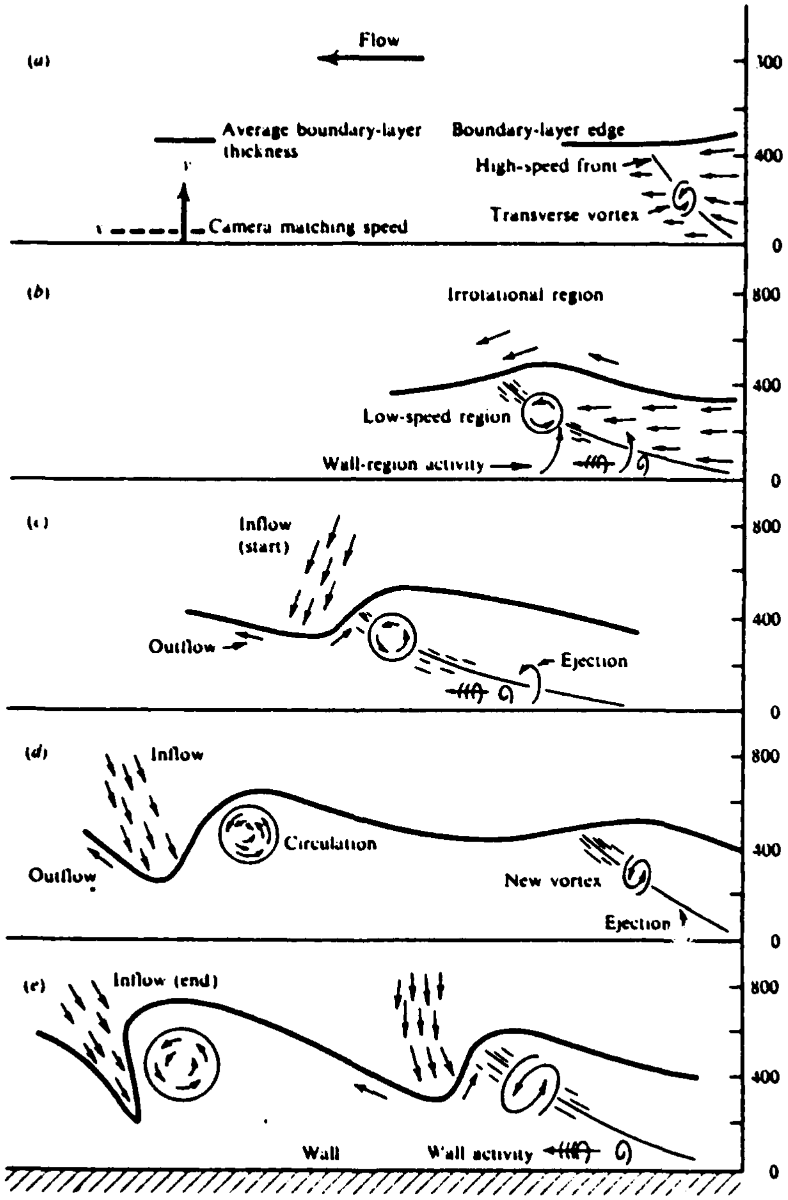


Fig. 12 Phenomenological model of the deterministic cycle of individual coherent events exhibited in steroscopic visual studies of a flat-plate turbulent boundary layer (from Ref. 23).

and discrete spectrum portions of the linear boundary layer response to a pulsed point-source; 2) evolve models descriptive of the long-time behavior of nonlinear wave packets and attendant mean flow distortions, which may be associated with the portions of the response, by jointly exploiting the near equilibrium viewpoint of Ref. 25 to reflect the near self-preserving behavior demonstrated in the experiments of Refs. 22, 23, and the viewpoint of matched solutions including spanwise-modulated nonlinear critical layers (as outlined above in connection with the transition problem) to reflect the strong vorticity concentrations exhibited in Fig. 12; 3) validate the models so obtained against the referenced experiments and, in the process, determine the natural bandpass filtering action of the two coexisting nonlinear wave packets, with attendant mean flow distortions, which leads to the single, cyclic, natural boundary layer response exhibited in Fig. 12; 4) combine those results and an analysis of secondary instabilities, intrinsic to either the structures so evolved or their interfaces, to identify the life-cycle of the single-pulse response pattern, the pulse-response repetition frequency and the attendant, time-averaged, mean flow constitutive relations. Clearly much detailed model development and validation remain to be accomplished. Whereas a single set of nonlinear wave processes dominate on physical grounds, conceptual and formal unity may be anticipated for the attendant mathematical models. As an example in this regard we refer to the previous discussion and model outline for the controlled transition problem and the attendant indication that the spanwise amplitude modulation intrinsic to the three-dimensional packet of nonlinear Tollmien-Schlichting waves necessarily leads to breakdown repetition, and cyclic process regeneration, such as indicated by the

qualitative experimental model of Fig. 12. Accordingly, we submit that the proposed viewpoint can successfully close the deterministic data interpretation/modeling loop for coherent structures in bounded as well as free transitional and turbulent shear flows.

Additional evidence could be presented, e.g. the explanation (Ref. 6) of the puzzling multiple stability regions observed in the high speed transition experiments of Ref. 26. However, we refrain from doing so in the belief that the above discussions suffice to illustrate the proposition that there are available novel, rapidly growing, basic physical understanding and modeling capabilities which provide a conceptually unified framework for first principle solutions to diverse, heretofore unrelated, turbulence problems and, thus, set a promising pattern of inquiry for future research. Only hastenly we reiterate the relevance of this research to long-standing as well as recently recognized applied problems wherefore rational, user-oriented, analyses and solutions are not available. In that general connection, and with specific reference to the multifaceted effects of coherent structures in turbulent flows discussed in this section, we present some experimental results for the atmospheric diffusion of a buoyant smoke plume, generated by a continuous oil fire (Fig. 13, Ref. 27). The meandering rise and fall of the plume must clearly be attributed to strong, organized, large-scale motions in the unstable atmospheric boundary later prevailing during the experiment. Whereas the time/space scales of the attendant visibility/obscuration pattern are significant from the viewpoint of practical electro-optical system operations, traditional, long-time averaged, turbulence models (which predict a smoothly rising plume) are distinctly inadequate for realistic system operation studies.

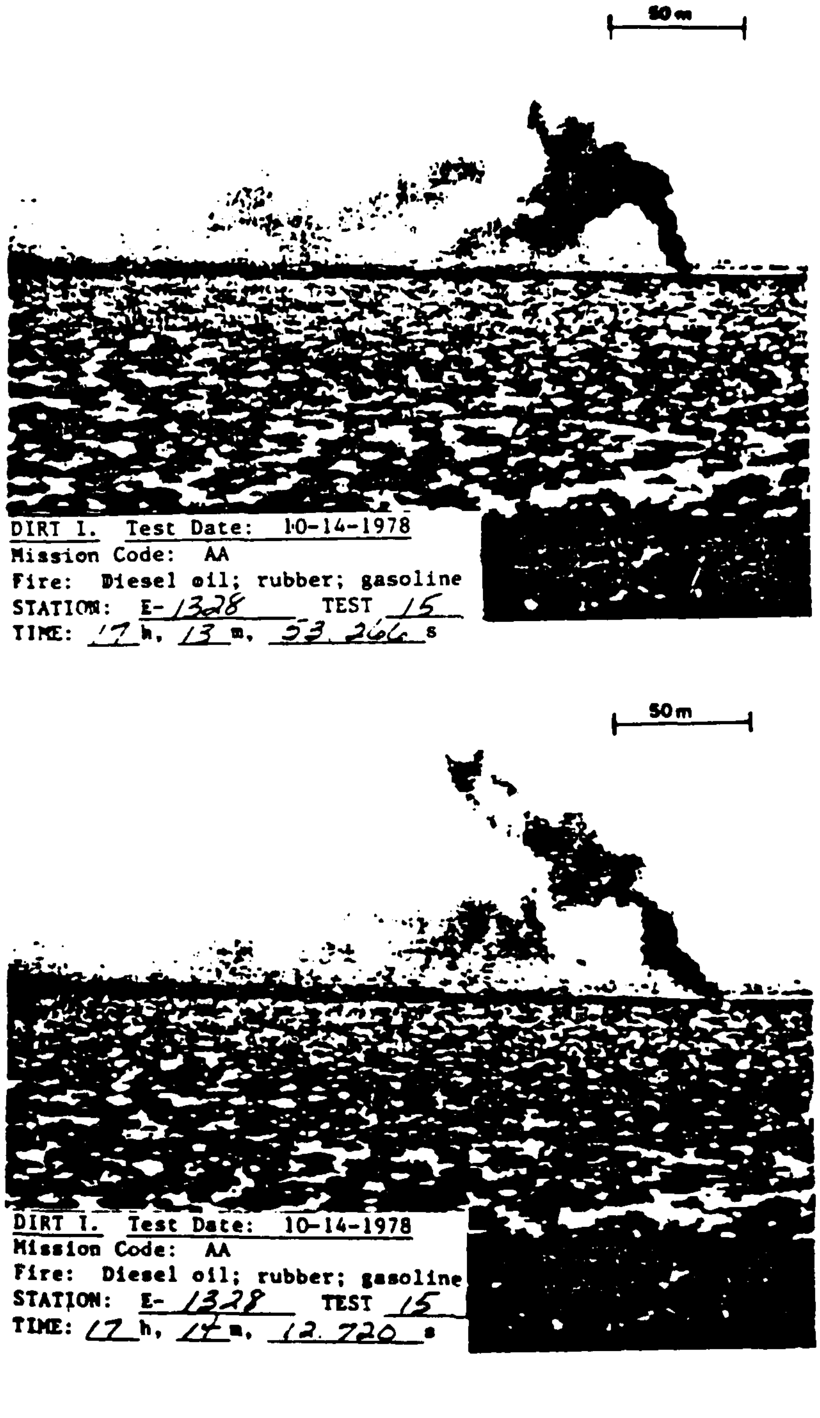


Fig. 13 Photographs of the smoke plume generated by a continuous oil fire at White Sands Missile Range. Large space/time scale meanderings (rise and fall) of the buoyant plume are due to coherent motions in the unstable atmospheric boundary layer prevailing during the experiment (from Ref. 27).

Since the pictures provide only two realizations of the plume pattern in a single viewing plane and for the specific conditions of the experiment, the cost and effort required to accumulate a statistically significant plume-pattern data-basis are clearly prohibitive. By contrast, the modeld outlined above are keyed to systematically yield such information and, thus, to provide a sound basis for operational analysis.

From an applications viewpoint we also note that the models under discussion provide a rational basis for evaluating, scaling and/or evolving novel flow control concepts, such as those explored in recent laboratory experiments with free shear layers (Ref. 28), and those successfully employed in at least one advanced flight vehicle air intake system (Ref. 29). In the former case large increments in shear layer growth, over considerable downstream distances, were obtained by oscillating the trailing edge of the splitter plate at selected amplitudes and frequencies. The forcing resulted in nonlinear vorticity concentrations characterized by lower shedding frequencies, but faster growth rates, than those which prevailed in the absence of forcing. A parametric amplifier response was clearly elicited. However, the "scaling" of such nonlinear response to other situations remains obscure so long as an adequate nonlinear model is not developed. The same is true for the case of the air intake system (Ref. 29), where an unusually compact diffuser design was achieved by building resonators into the diffuser wall. Apparently this device augments the bursting frequency in the boundary layer; as a result, the magnitudes of the mean stress/effective transports are increased, and the boundary layer's ability to withstand adverse pressure gradient is improved. Again, the concept is attractive, but its systematic application remains uncertain.

III. SUMMARY

The nonlinear wave interpretation and description of the large scale coherent structures commonly observed in free as well as bounded turbulent shear flows has been discussed. The experimentally observed cyclic development of nonlinear two-dimensional vorticity concentrations in homogeneous, incompressible, free mixing layers has been linked to the growth/equilibration of finite amplitude, spatially amplifying instabilities and their cyclic regeneration under the action of intrinsic secondary instabilities evoked by flow nonlinearity. The mathematical modeling of such nonlinear behavior in terms of matched asymptotic expansion solutions of the Navier Stokes equations, being reported under separate cover, has been reviewed. The relevance of the physical viewpoint and the mathematical model to more general turbulent flows has been examined and supported by an analysis of selected, conditionally sampled, measurements in transitional and turbulent boundary layers. On that basis, a dominant role of specific nonlinear wave processes has been indicated, and the approach to their systematic mathematical modeling from first principles has been outlined.

IV. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

In addition to the principal investigator, Dr. Roberto Vaglio-Laurin Professor of Applied Science, the following post doctoral fellows/ research scientists and graduate students/research assistants have participated in the research: Drs. V. Barra, G. Kleinstein, N.S. Liu, Messrs. C.L. Chou, J.P. Clesca, C.T. Hsien, R.F. Murphy and Y. Wey.

V. REPORTS/PAPERS PREPARED UNDER THE CONTRACT

Two reports have been prepared (Ref. 4 and the present one). A paper (Ref. 5) is being submitted for journal publication.

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